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Energy Management of Stand-alone Hybrid PV System

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Abstract

With the increasingly prominent energy crisis and environmental pollution, the solar energy as a new and clean energy, has attracted much attention. Battery has a disadvantage of over-current in the traditional topology of PV system. In this paper, a novel topology of a stand-alone hybrid PV system where battery is connected with a DC bus via a parallel controller is adopted to solve the problem. Constant-voltage and current-limited control are realized by parallel controller to meet the energy storage of the system requirement and to protect the battery. Super capacitor is used to filter the PV cell output and to reduce the small charging and discharging cycle of the battery. An energy management strategy of the PV system is proposed to achieve the normal operation of the system, and to ensure the battery working in the optimal state to extend the battery lifetime. Finally, the proposed energy management strategy is verified by the results of simulation.

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Keywords: PV system, energy management, battery, super capacitor, hybrid storage

1. Introduction

Recently, countries around the world pay attention to seeking a variety of renewable and clean alternative energy. Solar energy has attracted all the countries for the advantages such as clean, carbon-free and inexhaustible. It is suggested that solar power generation has a very broad prospect of development [1]-[5]. Stand-alone photovoltaic (PV) system is one of the most important applications in solar power generation, and has high practical value in the areas which is uncovered by power grid, such as remote area, desert and border outpost. However, the power of PV cell is greatly influenced by light intensity and temperature. In addition, PV cell cannot store energy by itself, thus a battery is required to balance the energy of the PV system [6]-[8].

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In the traditional stand-alone PV system, battery current is uncontrollable because battery and DC bus is connected directly. When the load changes abruptly, it often damages the battery due to a large battery current. Meanwhile, there is a small cycle of charging and discharging in the battery, which can give rise to the reduction of battery lifetime [9]-[10]. Currently, a super capacitor in parallel with the battery via a parallel controller is adopted to reduce battery current. However, as the battery is also connected directly with DC bus, there will be a short time of over current in the battery when the load and light intensity change abruptly.

In this paper, a novel topology of a stand-alone hybrid PV system that the battery is connected with a parallel controller is adopted to solve the problem of over current in the battery. Meanwhile, this paper proposes a new energy management strategy of stand-alone hybrid PV system by taking the advantage of the high charging and discharging speed of the super capacitor. The key point of the strategy is to control battery and super capacitor to operate in suitable modes according to the energy balance of the system, which can stabilize the voltage of DC bus to ensure the normal operation of power supply system, and make the battery working in an optimal charging and discharging status. The results of simulation verify the effectiveness and feasibility of the energy management strategy.

2. System Topology Design and Operation Modes

The main control device of the stand-alone hybrid PV system is the parallel controller through which battery and super capacitor is connected with the same DC bus. The objective is to control battery and super capacitor working in a proper mode separately, and protect the battery, ensure that the voltage of the DC bus is stable and the load is in normal operation. That is to say V_{bus}=constant, and $I_{b\text{-}min}<I_b<I_{b\text{-}max}$.

Generally, parallel controller can be divided into two control mode: active control and passive control. Passive control uses a diode to connect the energy storage element with the DC bus, which is simple but uncontrollable. While active control uses a DC-DC converter, which can realize flexible control of constant-voltage and current-limited based on the requirements of the stand-alone hybrid PV system. In this paper, energy management of stand-alone hybrid PV system is designed by an active parallel controller which is noted as boost/buck DC-DC converter. Fig. 1 shows the setup of stand-alone hybrid PV system topology.

The proposed stand-alone hybrid PV system which adopts a DC bus structure is composed of a photovoltaic cell, a battery, a super capacitor, a boost converter, a boost/buck convertor and the load. In the proposed system, the DC bus voltage is set V_{bus}, and the PV cell is connected with DC bus through the boost converter, which achieves the PV cell Maximum Power Point Tracking (MPPT) control. Super capacitor realizes constant-voltage control via the boost/buck converter to stabilize the DC bus voltage and filter the output of the PV cells. Battery is connected with the DC bus via the boost/buck convertor, and works in constant-voltage mode under fluctuating load. When the current is greater than the maximum current (I_{bmax}), the battery turns into current-limited mode to protect the security.

Constant-voltage mode is divided into boost constant-voltage and buck constant-voltage based on the PV cell power (Ppv) and the load power (P_0). If Ppv>P_0, the boost/buck convertor works in buck constant-voltage mode, battery and super capacitor absorb the excess energy; if Ppv<P_0, the boost/buck converter works in boost constant-voltage mode, battery and super capacitor release energy to the load. Similarly, current-limited mode is also divided into boost current-limited and buck current-limited, whose transition condition is consistent with constant-voltage mode.

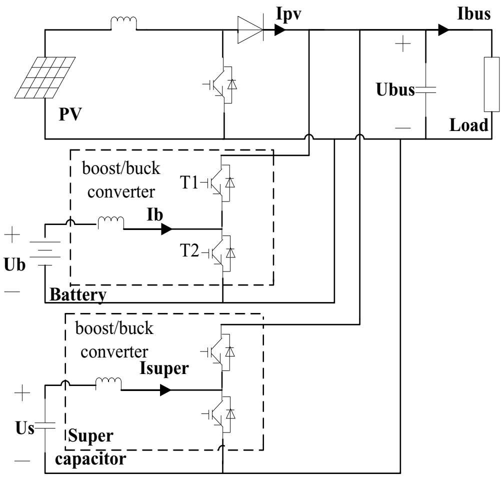


Fig. 1. Topology of stand-alone hybrid PV system

Table 1: Operation modes of the system

Current of the battery(I_b)	Power of PV cell and load			
	$P_{pv}>P_0$		$P_{pv}<P_0$	
$\lvert I_b \rvert > I_{b\max}$	Mode III battery: buck current-limited super: buck constant-voltage PV:MPPT	Mode III battery: buck current-limited super: buck constant-voltage PV:MPPT	Mode IV battery: boost current-limited super: boost constant- voltage PV:MPPT	Mode IV battery: boost current-limited super: boost constant- voltage PV:MPPT
$\lvert I_b \rvert < I_{b\max}$	Mode II battery: buck constant-voltage super: buck constant-voltage PV:MPPT	Mode II battery: buck constant-voltage super: buck constant-voltage PV:MPPT	Mode I battery: boost constant-voltage super: boost constant-voltage PV:MPPT	Mode I battery: boost constant-voltage super: boost constant-voltage PV:MPPT

Battery is the most important energy-storage component of stand-alone hybrid PV system, whose mode-switch is the key point of the design of energy management. The stand-alone hybrid PV system is divided into 4 operation modes, as shown in Table 1, based on the real-time value of P_{pv}, P_0, and the current of the battery I_b.

If I_b>0, the battery works in a discharging state, otherwise, the battery works in a charging state. I_{bmax} is the maximum current of the battery, which is also the mode-switch threshold current. In the proposed PV system, the maximum current is set to I_{bmax}. Super capacitor works in constant-voltage mode can minimize small charging and discharging cycle and filter the output of PV cells, while photovoltaic cell works in MPPT mode will maximize the use of solar energy. The energy flow diagrams of 4 operation modes for the stand-alone hybrid PV system are shown in Fig. 2.

Mode I:

Photovoltaic cell works in MPPT mode is used to maximize solar energy. When PV cell cannot provide enough energy to power load ($P_{pv}<P_0$), the shortage will be complemented by battery and super capacitor via the boost/buck converter. Battery and super capacitor works in boost constant-voltage mode is to stabilize DC bus voltage. As a result, energy flows from the storage to the DC bus and the storage

works in the discharging state.

Mode II:

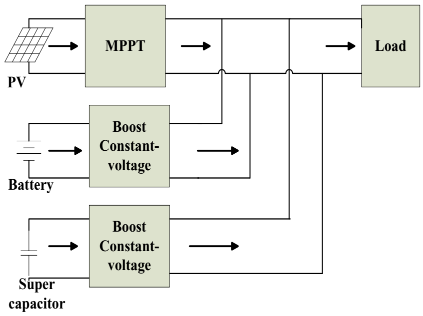
When the light gradually increases, and PV cell can provide more energy than the load required ($P_{pv}>P_0$), battery and super capacitor will absorb the excess energy. In this case, battery and super capacitor works in buck constant-voltage mode to ensure the DC bus voltage stable. Therefore energy flows from the DC bus to the storage and the storage works in the charging state.

Mode III

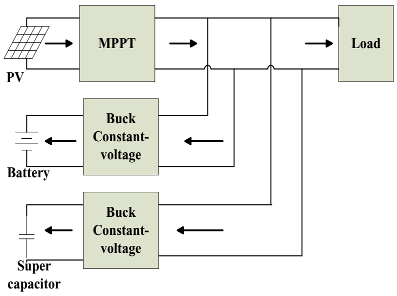
When the light further increases and the power output of PV cell (P_{pv}) is far higher than the load power (P_0), the battery current will exceed the maximum current ($I_b>I_{bmax}$). Then, battery turns into buck current-limited to protect the battery from being over current. Super capacitor could withstand high current without damaging its high power density, thus it continues workings in buck constant-voltage mode.

Mode IV:

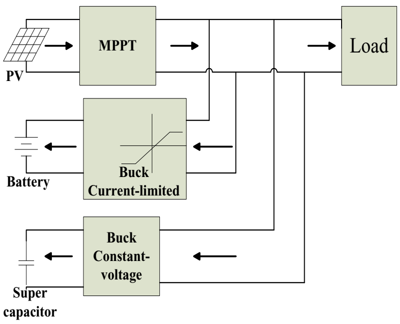
Battery and super capacitor works in boost constant-voltage mode at first. Then the light abruptly decreases or the load abruptly increases, the battery charging current will increase to stabilize the DC bus voltage. If $I_b>I_{bmax}$, battery should turn into boost current-limited mode to ensure the battery working in a proper discharging current.



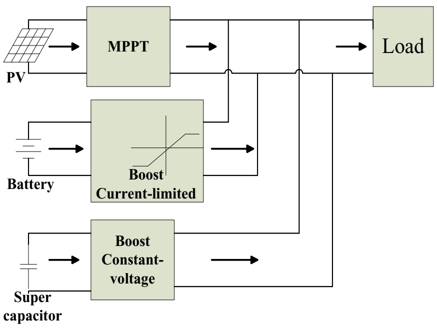
(a) Mode I



(b) Mode II



(c) Mode III



(d) Mode IV

Fig. 2. Energy flow of the system

3. Control Methods and Realization

From the analysis of the 4 modes of the stand-alone hybrid PV system above, three operation modes: PV MPPT control, constant-voltage and current-limited should be designed to achieve the energy management control and the stability of the system.

3.1. PV MPPT control

MPPT control technology is widely used in the application of solar power generation [11]-[15]. Perturb and observe method, which is the most widely useful method of MPPT control, is adopted in this paper. PV cell output characteristics curve of light density and temperature are shown in Fig. 3.

As shown in Fig. 3, an output voltage of PV cell can be determined in a certain condition, whose corresponding power is the maximum output power. If the working point is on the left of the maximum power point, *dP/dV>0*; and if the working point is on the right of the maximum power point,

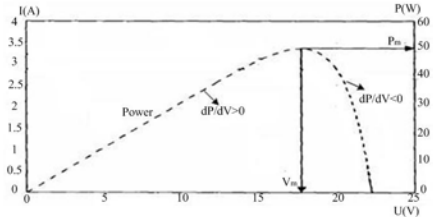


Fig. 3. Output characteristic curve of PV cell

dP/dV<0. According to the characteristics above, the control process of the perturb and observe method is that: First, set up a PV cell operation voltage, then give some periodic disturbance to the PV cell by adjusting the duty cycle of the boost converter, such as to increase, then compare the PV output power with before, if the output power increases, that means it works in the left of the maximum power point, we should continue to maintain the disturbance direction to increase the output voltage, otherwise, if the output power decreases, that means it works in the right of the maximum power point, the disturbance direction will away from the maximum power point, thus it should change the disturbance direction to decrease the output voltage of PV cell. After the repeated adjustment, finally, the maximum power point will be found.

3.2. Constant-voltage Control and Current-limited Control

The boost/buck converter is shown in the dashed box of Fig. 1. When T1 is closed, T2 is open, the converter is equivalent to a boost circuit, battery and super capacitor discharges to the DC bus. When T2 is closed, T1 is open, it works as a buck circuit to control the duty cycle of T1 to achieve buck chopper by the anti-parallel diode of the IGBT (Insulated Gate Bipolar Transistor), energy flows from the DC bus to storage, battery and super capacitor will be in a charging state.

The control of the converter is shown in Fig. 4, and boost circuit and buck circuit use the dual loop control. The inner loop control is current-limited control and the outer loop control is constant-voltage control. The outer loop control stabilizes the DC bus voltage (U_{bus}). U_{bus} is compared with a given voltage value (U_{ref}), then after a PI regulator and other process to get a given current value to the inner loop control. The inner loop control ensures the current of the battery (I_b) not to exceed the maximum current (I_{bmax}). The given current from the outer loop goes through a current-limited regulator. If the current is larger than maximum current, the output is changed into the maximum current, otherwise, the output is unchanged. Then the final given current I_{ref} of the current-limited control is determined, and the PWM signals of the IGBT by the PI regulator are obtained to achieve the current-limited control. If only the constant-voltage control is needed, the current-limited regulator could be removed to achieve the only constant-voltage control.

Battery uses constant-voltage and current-limited control, for the current cannot be too large. However, the super capacitor uses the constant-voltage control only, because it can withstand large current without damaging its high power density. When battery is in the current-limited control, super capacitor should ensure the stability of the DC bus voltage to maintain the system energy balance.

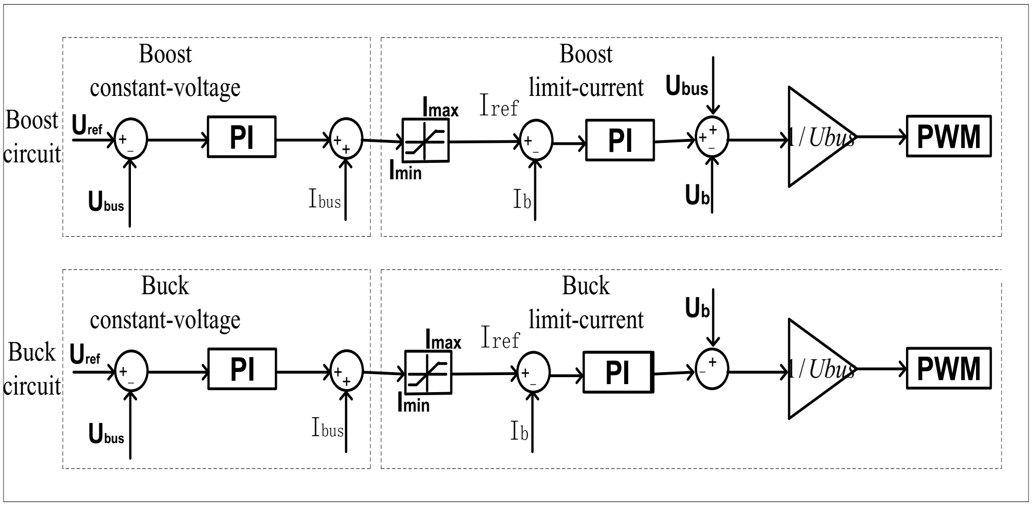


Fig. 4. Control block diagram of the boost/buck converter

4. Verification of Energy Management Strategy

In order to verify the feasibility and effectiveness of the proposed stand-alone PV system energy management strategy, a simulation model is designed according to the topology shown in Fig.1, and the simulation parameters of the system are shown in Table 2.

Table 2: Parameters of the system

Battery	Rated Capacity	65(A.h)
	Rated Voltage	70(V)
	Maximum Current	1.5(A)
Super Capacitor	Capacitance	70(F)
	Rated Voltage	70(V)
DC Bus	Voltage	100(V)

Fig. 5 shows PV system operation waveforms of I_{bus}, I_{bat}, I_{super}, U_{pv} and U_{bus} when the load abruptly decreases and then abruptly increases. PV cell cannot provide enough energy to power the load ($P_{pv}<P_0$) before the time 0.1s. Thus, battery and super capacitor works in the boost constant-voltage state to power the load simultaneously, and the DC bus voltage (U_{bus}) is 100V. Then the load abruptly decreases at the time 0.1s, PV cell can provide more energy than the load needed, thus battery and super capacitor turns into buck constant-voltage control to absorb the excess energy, and PV system works in mode II state. PV cell energy is insufficient at the time 0.2s as the load abruptly increases again, then PV system works back to mode I state, and the DC bus voltage is still stabilized at 100V. Therefore, PV system can work properly in mode I state and mode II state, battery and super capacitor work between charging and discharging state freely to stabilize the DC bus voltage.

Fig. 6 shows PV system operation waveforms of I_{bus}, I_{bat}, I_{super}, U_{pv} and U_{bus} when the load abruptly increases and then abruptly decreases, and battery works in discharging state all the time. Energy of PV cell is insufficient, then battery and super capacitor works in boost constant-voltage before the time 0.1s, and PV system works in mode I state. The current of the battery is less than the maximum current (1.5A), for the load is not very large. The load abruptly increases and the current of battery and super capacitor also increase at the time 0.1s. When the current reaches the maximum value, battery turns into current-limited control, and the current is limited in 1.5A to protect the safety of the battery. While the super capacitor provides all the insufficient energy of the system required, then PV system works in mode IV state. When the load abruptly restores at the time 0.2s, PV system works back to mode I state, and then the battery turn back to constant-voltage state, the DC bus voltage is also stabilized at 100V in the whole time.

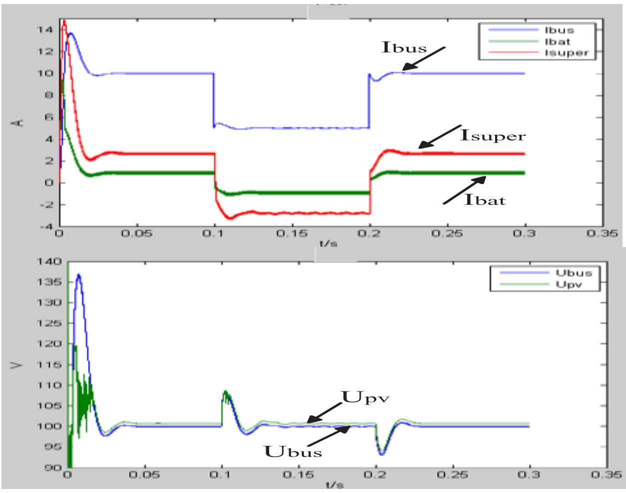


Fig. 5. Operation waveforms of the changes between mode I and mode II

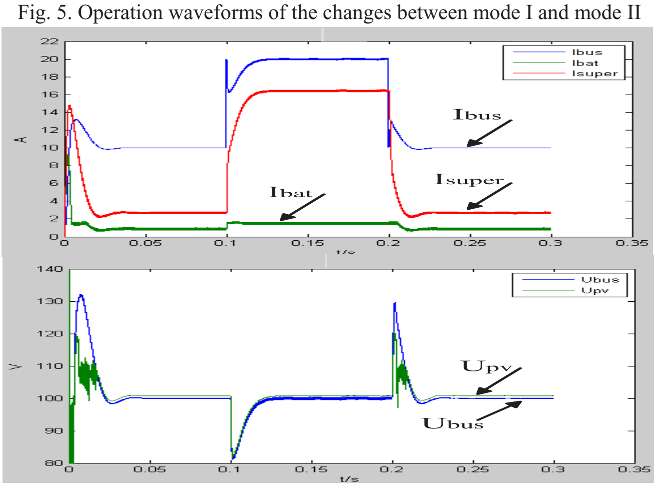


Fig. 6. Operation waveforms of the changes between mode I and mode IV

Fig. 7 shows PV system operation waveforms of I_{bus}, I_{bat}, I_{super}, U_{pv} and U_{bus} when the load abruptly decreases and then abruptly increases, and battery works in charging state all the time. Battery and super capacitor work in buck constant-voltage state before the time 0.1s, because PV cell can provide more energy than the load needed. When the load decreases at the time 0.1s, the current of the battery will increase to absorb more excess energy to stabilize DC bus voltage, and PV system works in mode II state. The battery turns into current-limited control as the battery current exceeds the maximum current (1.5A), the extra energy is absorbed by the super capacitor to stabilize the DC bus voltage, PV system works in mode III state. When the load abruptly restores at the time 0.2s, PV system works back to mode II state, and battery turns back into constant-voltage control as the current drops.

The simulation result shows that the system can work properly in all modes state, and switch automatically among different modes state. When the load abruptly decreases or increases, PV system can work in a proper mode state to stabilize the DC bus voltage and protect the battery. The effectiveness and feasibility of the proposed energy management of the stand-alone hybrid PV system is verified.

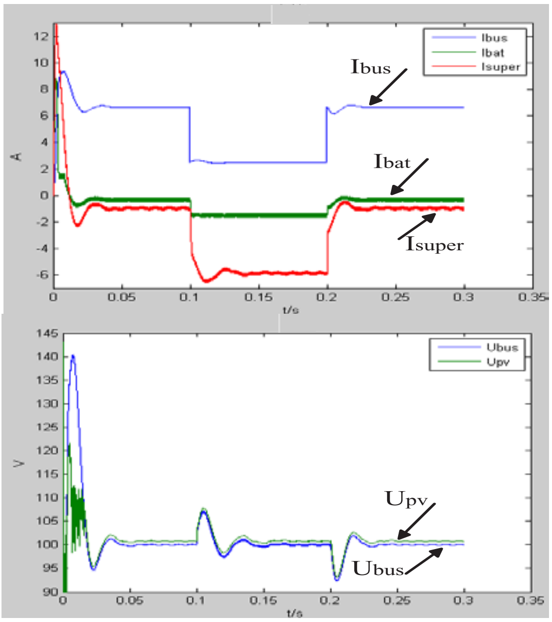


Fig. 7. Operation waveforms of the changes between mode II and mode III

5. Conclusion

This paper proposes the topology and energy management strategy of a stand-alone hybrid PV system, which can solve the over-current problem of the battery, and verifies the effectiveness and feasibility of the energy management strategy by the simulation results. The system has several advantages as following: 1) The battery is connected with the DC bus by a boost/buck converter, which can realize the constant-voltage and current-limited control of the battery. The battery can not only work in optimal charging and discharging state, but also satisfy the energy storage requirements of the system. 2) Super capacitor and battery hybrid energy storage can make full use of the large power density of super capacitor and the large energy density of battery to stabilize the stand-alone PV system. 3) PV cell use the MPPT control, which can maximize the use of the solar energy.

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